



New force and the LHC

Hye-Sung Lee
(Brookhaven National Lab)



Colloquium at the University of Kansas
Feb 22, 2010



Long title:

Why a **New force** should be discovered
at the **LHC**, and what we can do with it

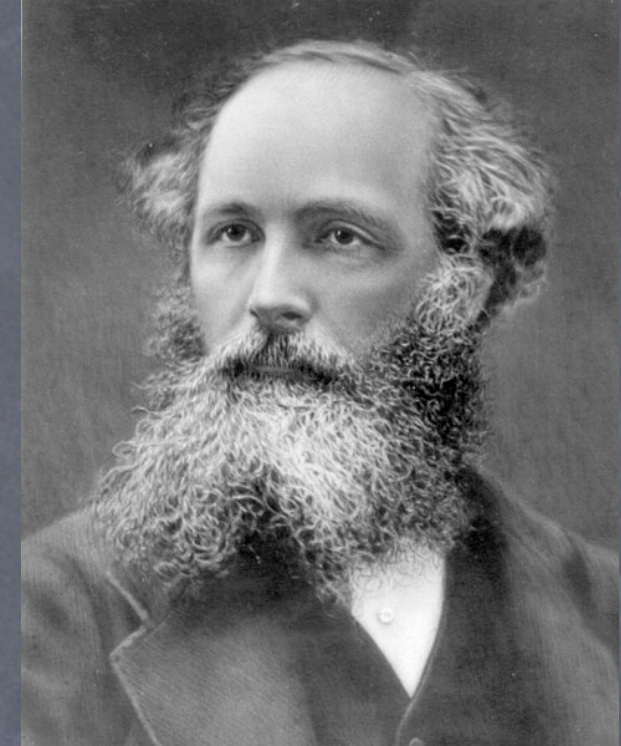
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$$F = ma$$



Fundamental forces known to us:

- (1) Gravity [I. Newton, ... in 17C]
- (2) Electromagnetic force [J. Maxwell, ... in 19C]
- (3) Weak nuclear force [S. Weinberg, ... in 20C]
- (4) Strong nuclear force [M. Gell-Mann, ... in 20C]



$$F = ma$$

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“Where do we go from here?”

$$F = ma$$

Fundamental forces known to us:

- (1) Gravity [Isaac Newton, ... in 17C]
- (2) Electromagnetism [James Clerk Maxwell, ... in 19C]
- (3) Weak nuclear force [S. W. Lee, ... in 19C]
- (4) Strong nuclear force [M. Gell-Mann, ... in 19C]

Option 1. Try to "unify" all forces.

Option 2. Try to find "another" force.

"Where do we go from here?"

5th force
: my topic today!

Physics is not Lotto.



We need a **motivation** to search for a New force.

Outline

1. Why Supersymmetry?


: Brief overview of particle physics

2. Supersymmetry calls for a New force

: Motivation of a New gauge symmetry

3. What can we do with a New force at LHC?

: Overview of my LHC research



The motivation
of 5th force

1. Why Supersymmetry?

Standard Model (SM)

Spin 0

"Scalar"

Higgs (H)

Spin 1/2

"Fermions"

Quarks (Q), Leptons (L)

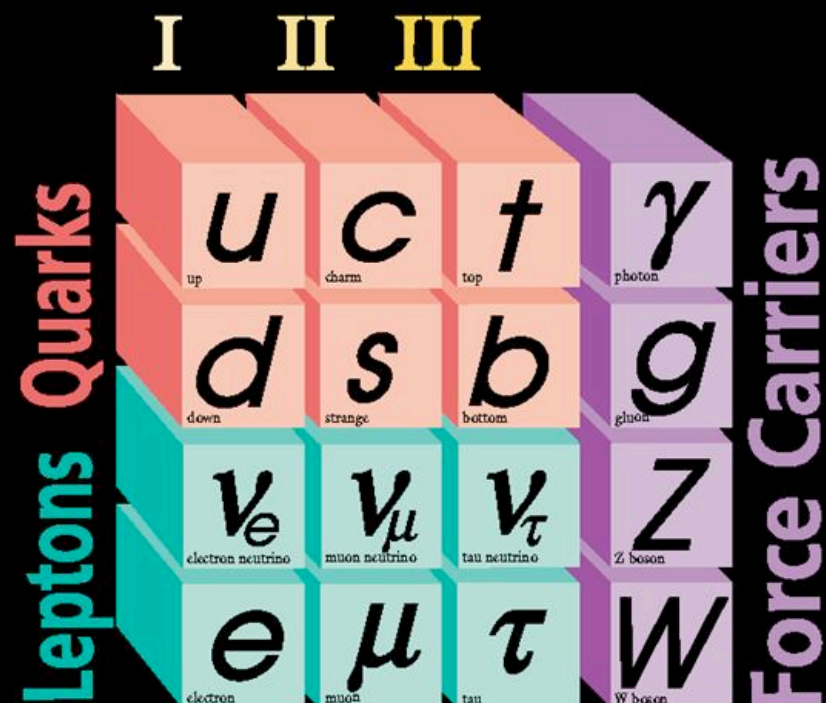
Spin 1

"Gauge bosons"

Photon (γ), Gluon (g), Z/W

The Standard Model of Particle Interactions

Three Generations of Matter



Gauge symmetry = $SU(3) \times SU(2) \times U(1)$
(All known forces except for Gravity)

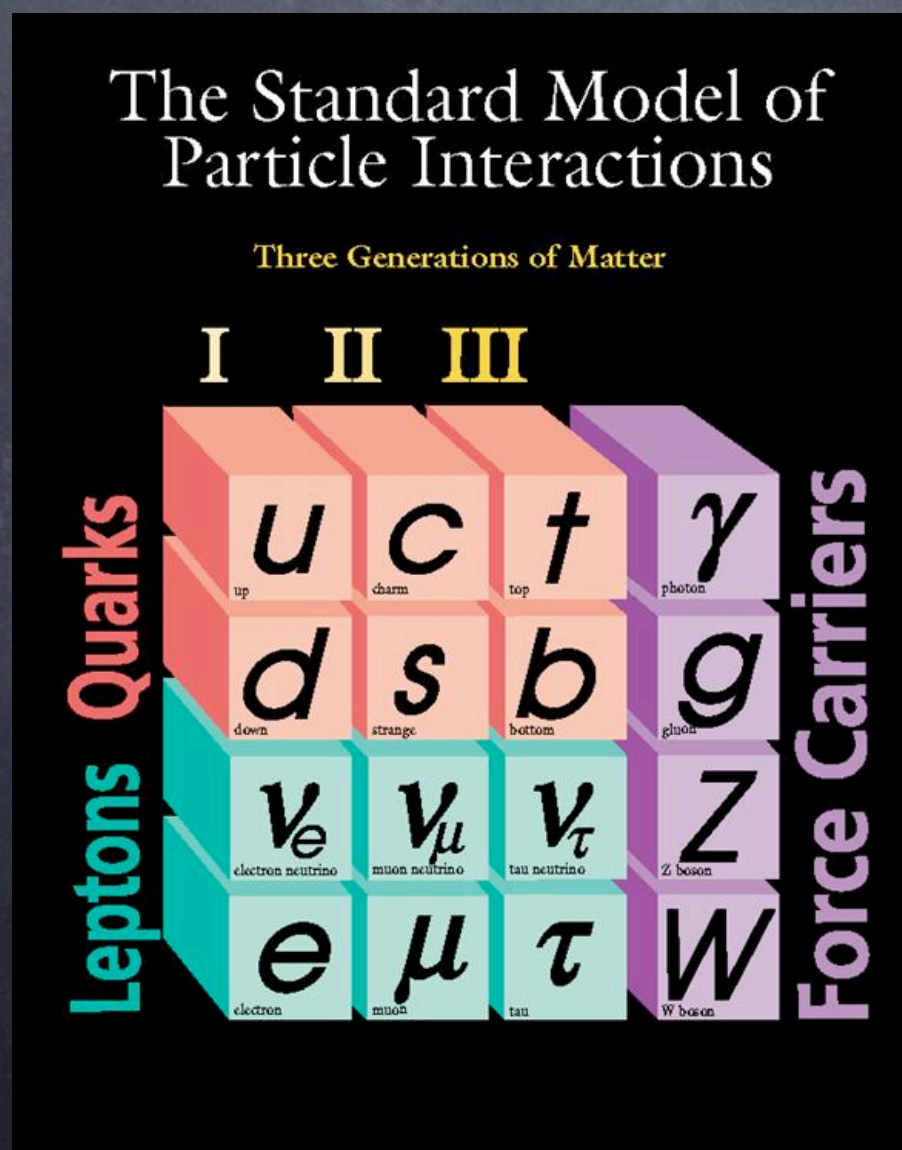
No gravity in SM

$$F = G_N \frac{Mm}{r^2}$$

$G_N = 10^{-10}$ [MKS] --> Neglect Gravity.
(SM is valid up to $r \approx 10^{-35}$ m)

Standard Model (SM)

Spin 0	"Scalar"	Higgs (H)
Spin 1/2	"Fermions"	Quarks (Q), Leptons (L)
Spin 1	"Gauge bosons"	Photon (γ), Gluon (g), Z/W



Gauge symmetry = $SU(3) \times SU(2) \times U(1)$
 (All known forces except for Gravity)

Strong force

Weak force

EM force

Standard Model (SM)

Spin 0	"Scalar"	Higgs (H)
Spin 1/2	"Fermions"	Quarks (Q), Leptons (L)
Spin 1	"Gauge bosons"	Photon (γ), Gluon (g), Z/W

Gauge symmetry = $SU(3) \times SU(2) \times U(1)$
(All known forces except for Gravity)

Higgs: the only undiscovered particle and
the only scalar (spin 0) particle.

Higgs scalar can explain the masses of the
fermions and gauge bosons (otherwise, massless).

Standard Model (SM)

Spin 0	"Scalar"	Higgs (H)
Spin 1/2	"Fermions"	Quarks (Q), Leptons (L)
Spin 1	"Gauge bosons"	Photon (γ), Gluon (g), Z/W

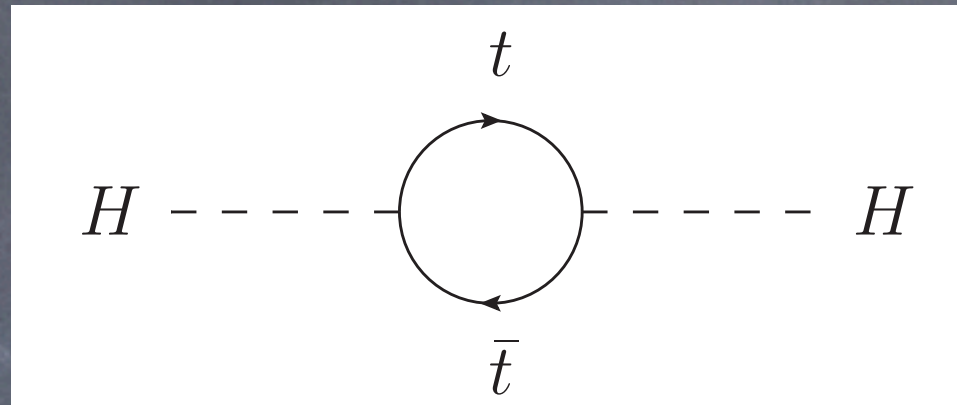
Gauge symmetry = $SU(3) \times SU(2) \times U(1)$
(All known forces except for Gravity)

Higgs: the only undiscovered particle and
the only scalar (spin 0) p

**Major discovery
goal at LHC**

Higgs scalar can explain the masses of the fermions and gauge bosons (otherwise, massless).

Higgs is a solution and a problem



Quantum correction to Higgs mass :

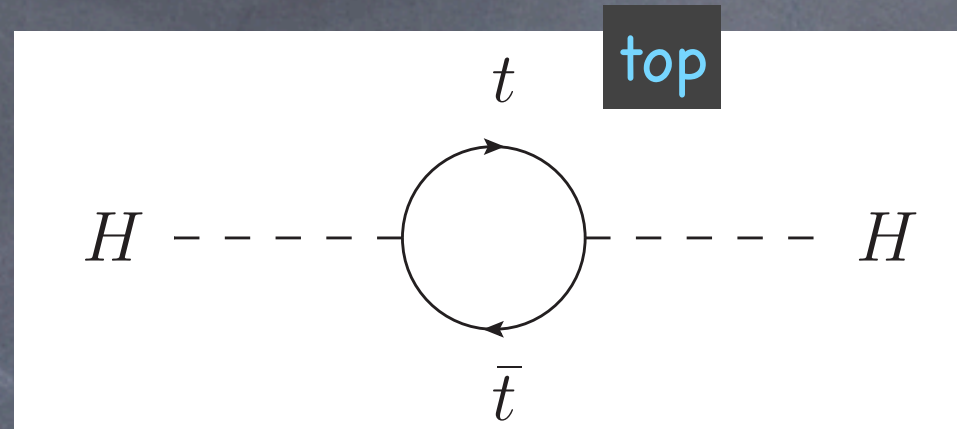
- Higgs borrows ENERGY for a short TIME and returns.
- It contributes to the Higgs mass.

Heisenberg's
Uncertainty Principle

$$\Delta E \Delta t \gtrsim \frac{\hbar}{2}$$



Higgs is a solution and a problem



$$\delta m_H^2(\text{top}) = -\Lambda^2 + \dots \quad (\Lambda = \text{cutoff scale of theory})$$

$= 10^{19} \text{ GeV}$
(SM valid up to 10^{-35} m)

$$m_{H_{\text{physical}}}^2 = m_{H_0}^2 + \delta m_H^2 = m_{H_0}^2 - (10^{19} \text{ GeV})^2$$

Expected Higgs mass = $O(10^{19} \text{ GeV})$

But, physical Higgs mass should be $O(100 \text{ GeV})$

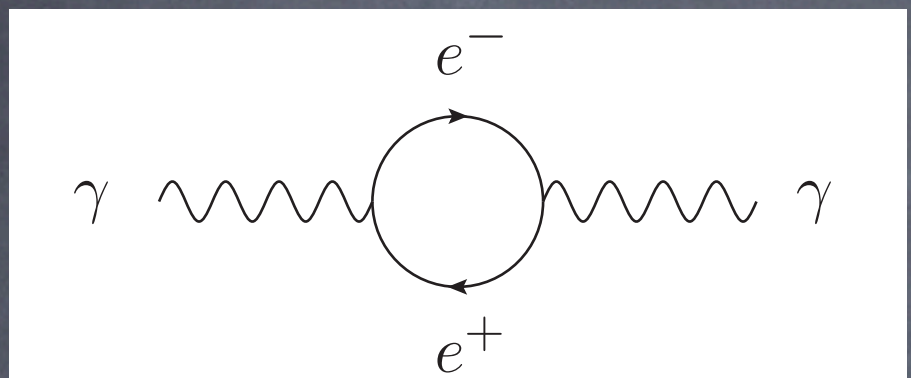
[Hierarchy problem]: Divergence (Λ^2) in scalar mass²

Something is missing.

(Proton mass $\approx 1 \text{ GeV}$)

What about other particles?

- Spin 1 particle (gauge boson):

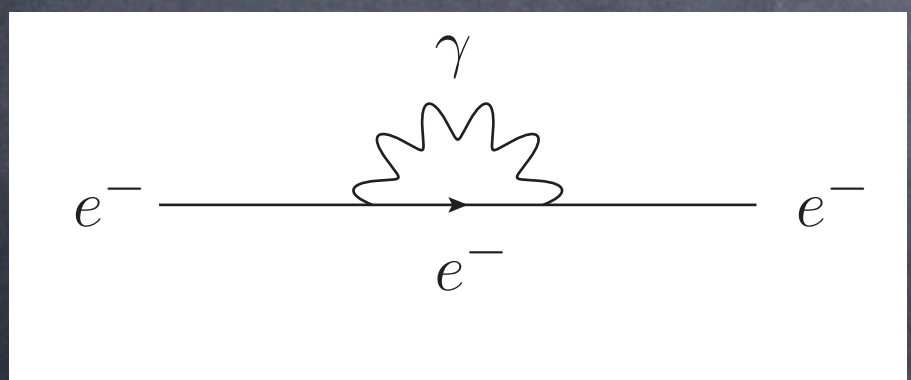


A Feynman diagram showing a vacuum polarization loop. Two wavy lines, labeled γ , enter and exit a circular loop. The top half of the loop is labeled e^- with a clockwise arrow, and the bottom half is labeled e^+ with a counter-clockwise arrow. To the right of the diagram is the equation $= 0$.

OK!

“Spin 1 particle mass is **protected by gauge symmetry**.”

- Spin 1/2 particle (fermion):



A Feynman diagram showing a fermion self-energy loop. A horizontal line with an arrow pointing right, labeled e^- at both ends, has a wavy loop attached to it. The loop is labeled γ at the top. Below the loop, the label e^- is present. To the right of the diagram is the equation $= (\text{very small})$.

OK!

“Spin 1/2 particle mass is **protected by chiral symmetry**.”

Look for a **new symmetry** to protect
spin 0 particle (Higgs scalar) mass.

Supersymmetry (SUSY)

SUSY: fermion (spin 1/2) \leftrightarrow boson (spin 0, 1)

SUSY predicts "Superpartners" (same quantum number except for spin).

Spin 0	Higgs (H)	Spin 1/2	Higgsino (\tilde{H})
Spin 1/2	Quark (Q), Lepton (L)	Spin 0	Squark (\tilde{Q}), Slepton (\tilde{L})
Spin 1	γ , g, Z/W	Spin 1/2	$\tilde{\gamma}$, \tilde{g} , \tilde{Z}/\tilde{W}

[SM particles]

[Superpartners]

Supersymmetry (SUSY)

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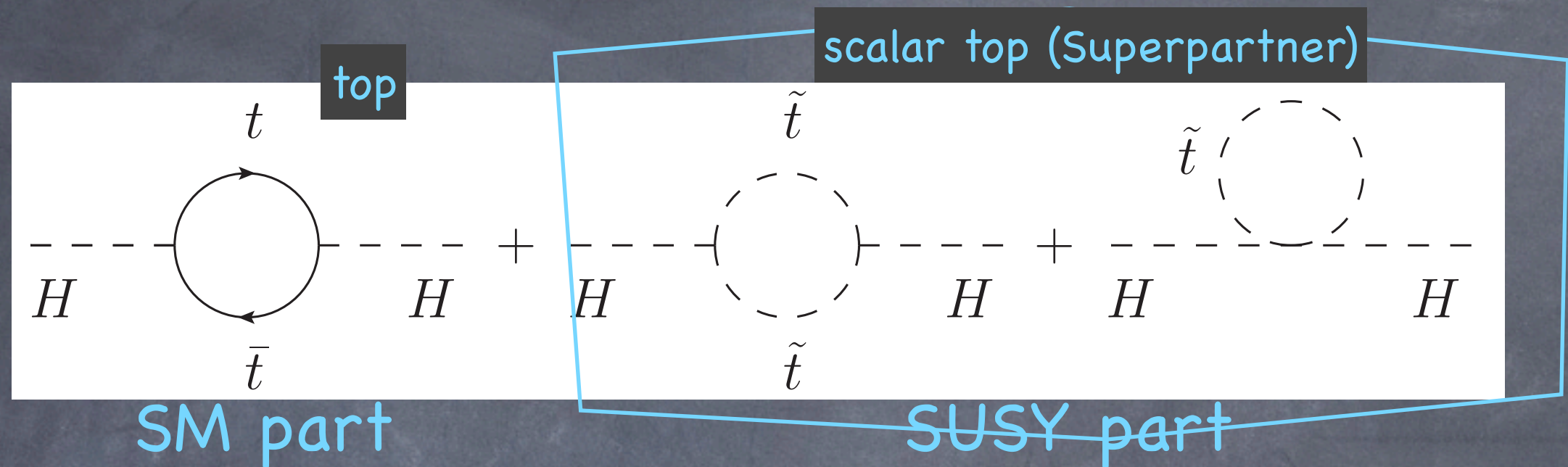
Provides
Dark Matter
candidate

Spin 0	Higgs (H)	Spin 1/2	
Spin 1/2	Quark (Q), Lepton (L)	Spin 0	Squark (\tilde{Q}), Slepton (\tilde{L})
Spin 1	γ , g, Z/W	Spin 1/2	$\tilde{\gamma}$, \tilde{g} , \tilde{Z}/\tilde{W}

[SM particles]

[Superpartners]

Higgs problem motivates Supersymmetry



$$\begin{aligned} \delta m_H^2(\text{top} + \text{stop}) &= (-\Lambda^2 + \dots) + (\Lambda^2 + \dots) \\ &= -m_{\tilde{t}}^2 \log(\Lambda/m_{\tilde{t}}) + \dots \end{aligned}$$

Divergence (Λ^2) cancelled!

"Spin 0 particle (Higgs scalar) mass can be protected by Supersymmetry."

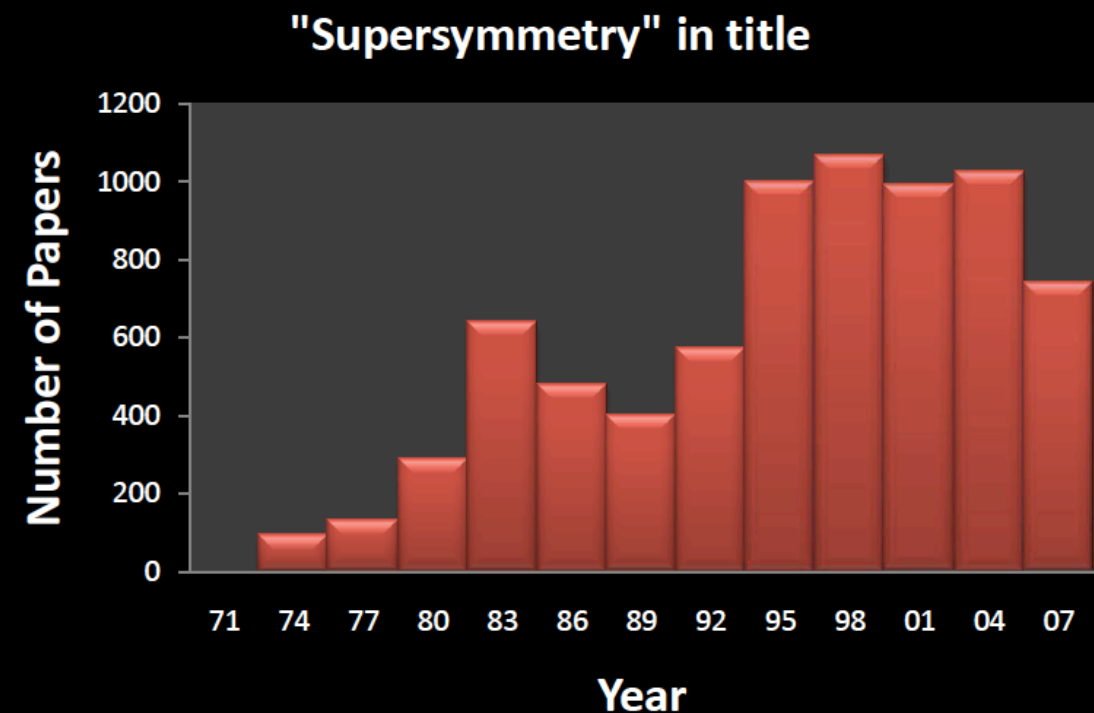
Supersymmetry in literature

Although there are other ideas ...

SPIRES database search results

“Supersymmetry” in title 7400 papers

“Higgs” in title 9000 papers



Supersymmetry in literature

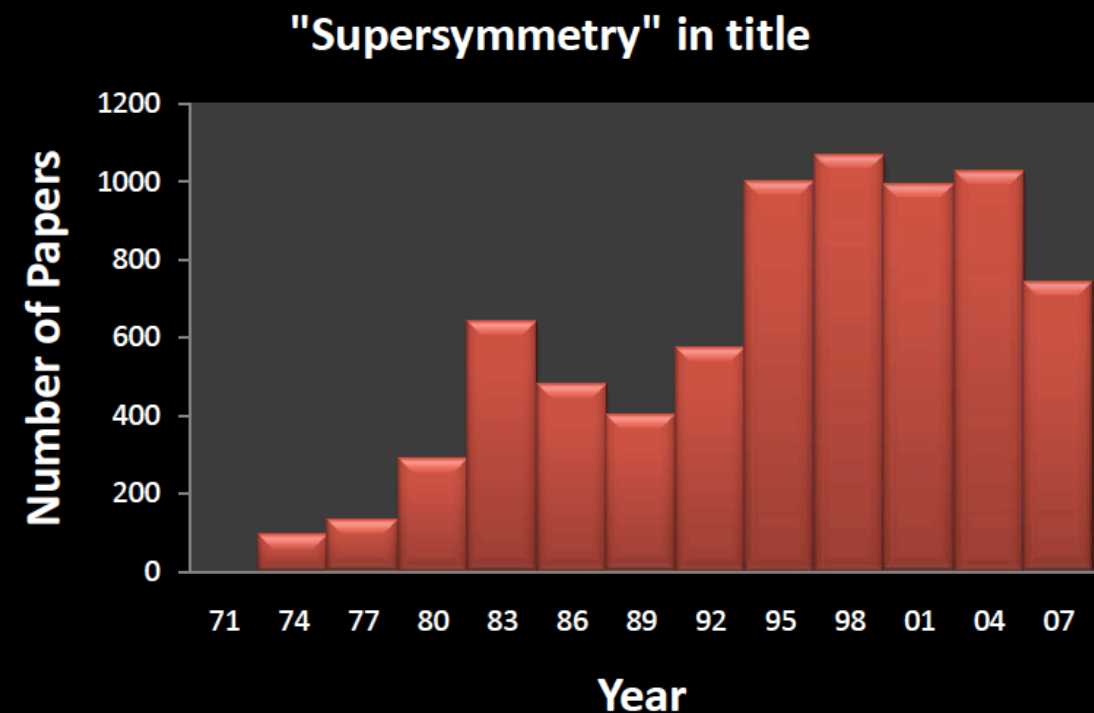
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SPIRES database search results

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**Another major
discovery goal
at LHC**

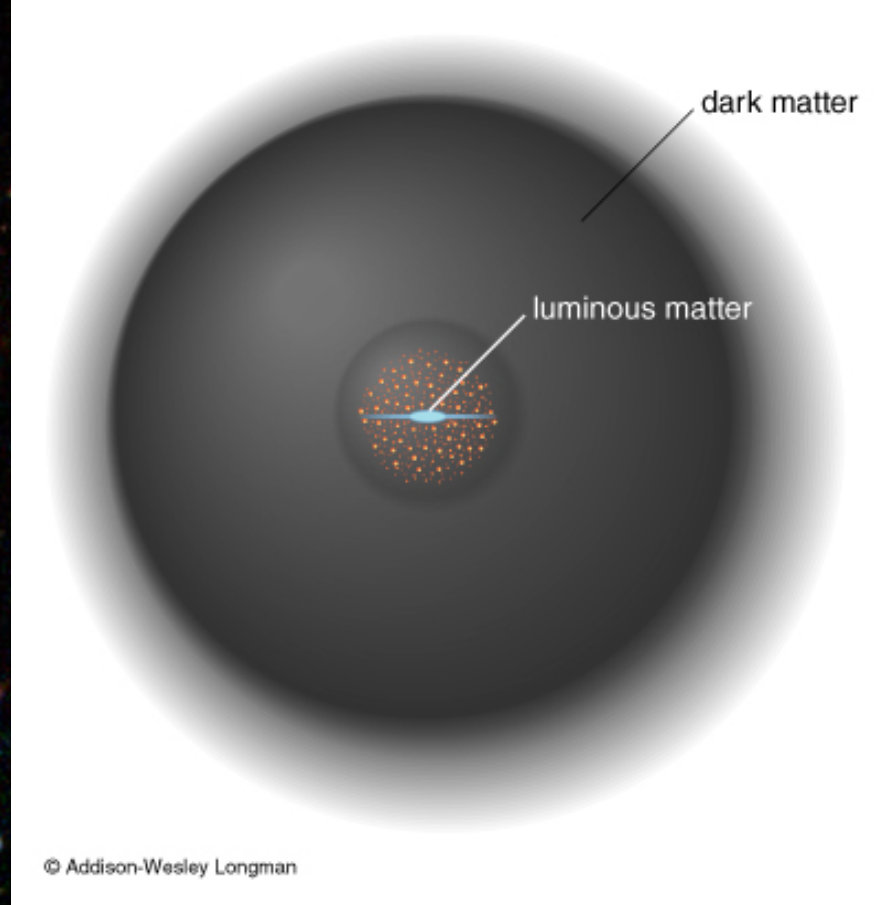


2. Supersymmetry calls for
a New force

Naive implementation

Standard Model + Supersymmetry ?

--> There are some Problems.

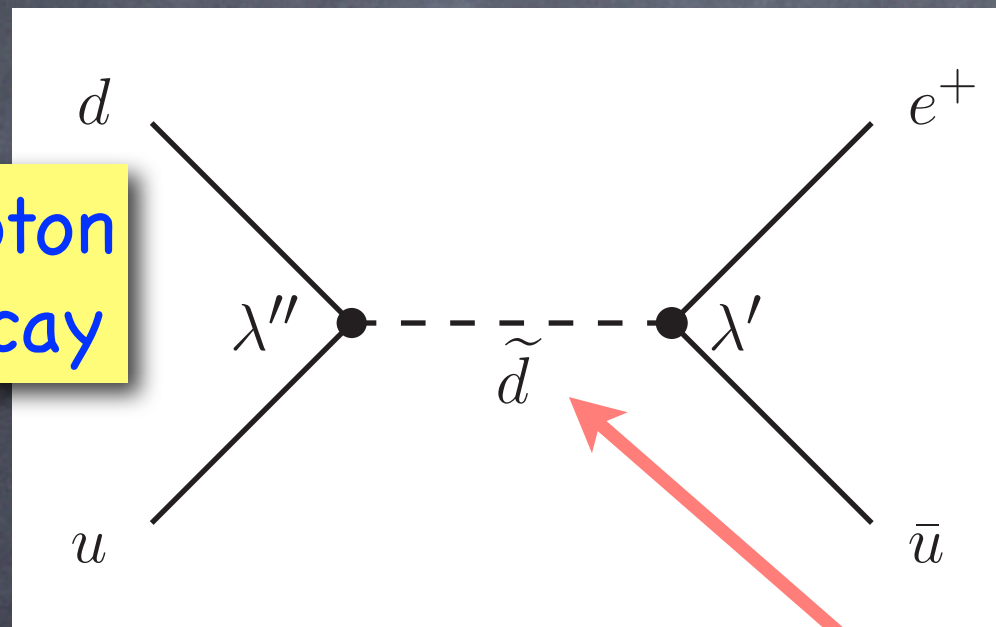


Universe = Bright world + Dark world
(Proton, etc) (Dark matter)

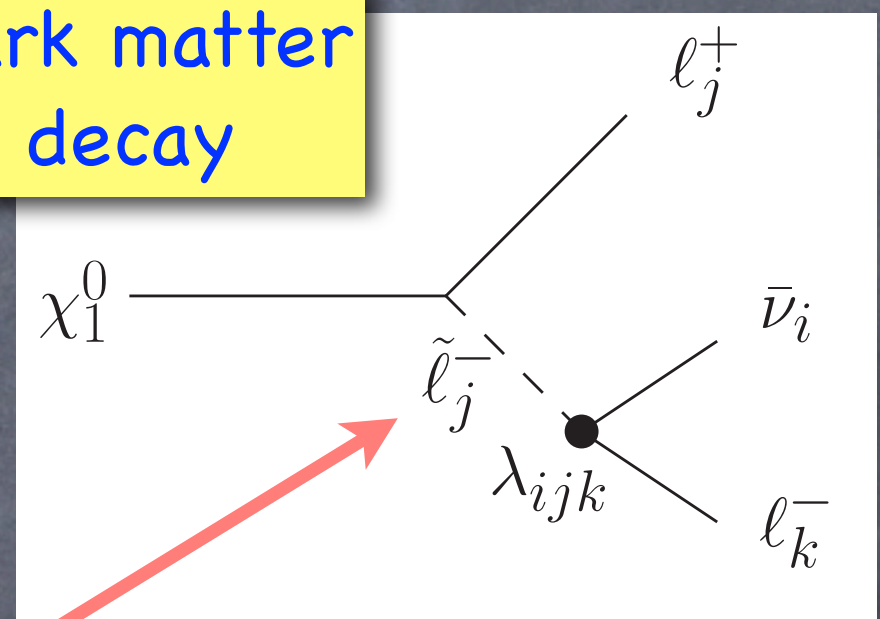
Building-blocks of Universe
(should be stable)

Building-blocks decay fast under Supersymmetry

Proton decay



Dark matter decay



Superpartners

Supersymmetry makes "Proton" and "Dark matter candidate" decay too fast.

We need something

Standard Model + Supersymmetry + "Something"

To address proton &
dark matter stability

It is like
we need Reins to control a Horse



We need "Something" to control Supersymmetry.
(Otherwise, building-blocks would decay fast)

Popular and old model

Standard Model + Supersymmetry + **R-parity** ?

Popular since it was adopted by
the First Supersymmetry model
(a.k.a. MSSM) [1981]



Popular and old model

Standard Model + Supersymmetry + **R-parity** ?

R₂ or R-parity (= Superpartner parity)

SM particles : even parity

Superpartners : odd parity

Proton : Leading order decay forbidden

Lightest Superpartner (DM candidate) : Stable

But, R-parity is Not perfect

Some issues of the R-parity:

1. Still insufficient proton stability [Weinberg (1982)]
[Proton still decays fast by (non-renormalizable) sub-leading order term]
2. Unnecessarily forbidden processes
[Forbidding either Lepton # or Baryon # is enough]
3. Limited dark matter property
[Recent cosmic data (PAMELA, Fermi) favors larger leptonic coupling]
4. Other theoretical issues
[Other issues such as mu-problem are not addressed]

But, R-parity is Not perfect

Alternative to R-parity?

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$U(1)_{[B-\frac{1}{3}L]}$

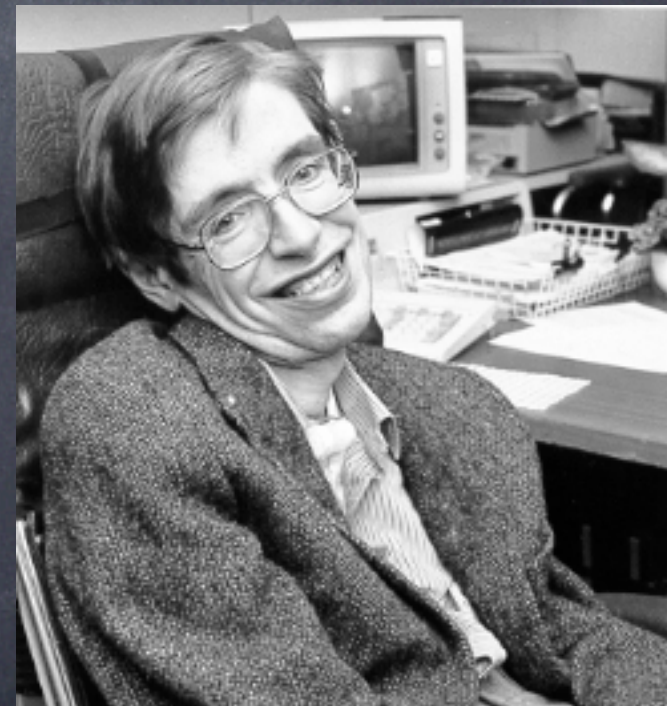
$U(1)_{[B_3]}$

$U(1)_{[U_2]}$

Besides, Gravity effect may explicitly break all global symmetries. [Hawking (1987)]

Even R-parity should exist only as a subgroup of a $U(1)$ gauge symmetry.

Typically, $U(1)_{[B-L]}$



But, R-parity is Not perfect

Alternative to R-parity?

Some issues of the R-parity:

1. Still insufficient proton stability [Weinberg (1982)]

The point is

“U(1) gauge symmetry” appears to be the best candidate of “Something” to control Supersymmetry.

Even R-parity should exist only as a subgroup of a U(1) gauge symmetry.

Typically, U(1)_[B-L]

[B₃]



Best-motivated Supersymmetric model

Standard Model + Supersymmetry + $U(1)$ gauge

Best-motivated Supersymmetric model

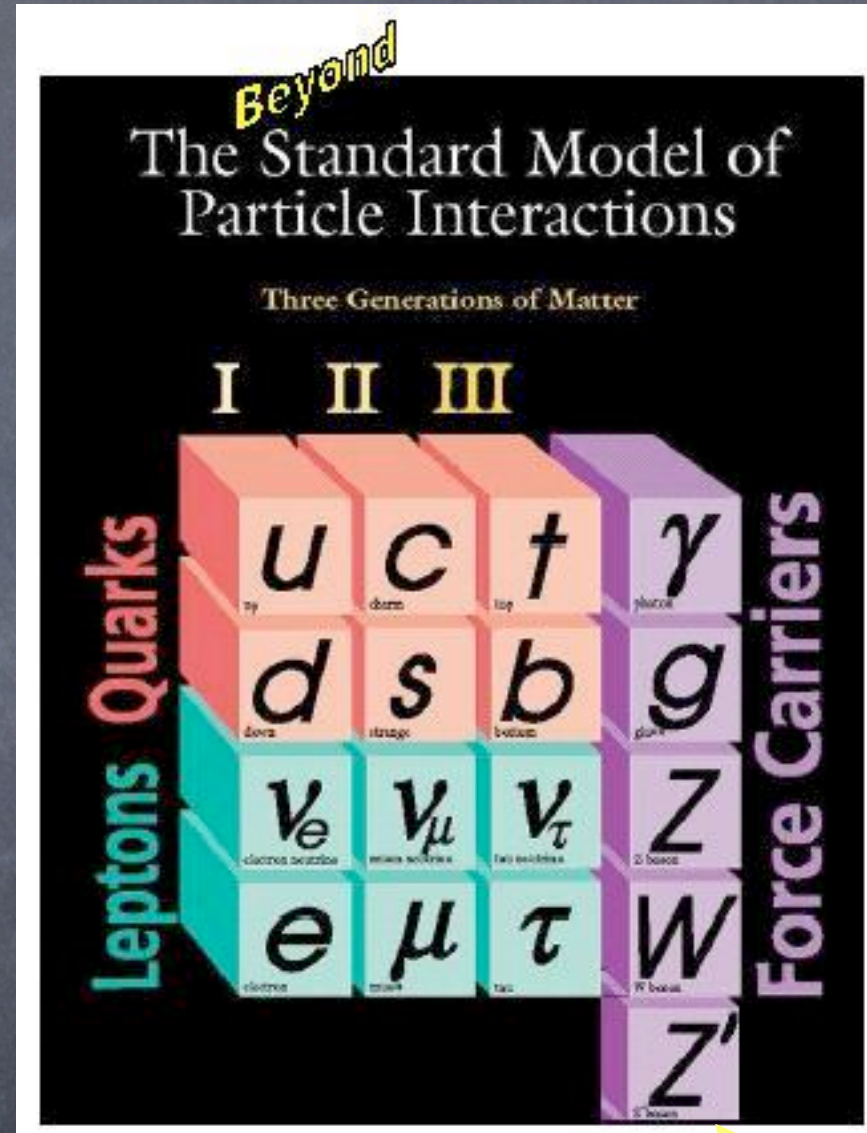
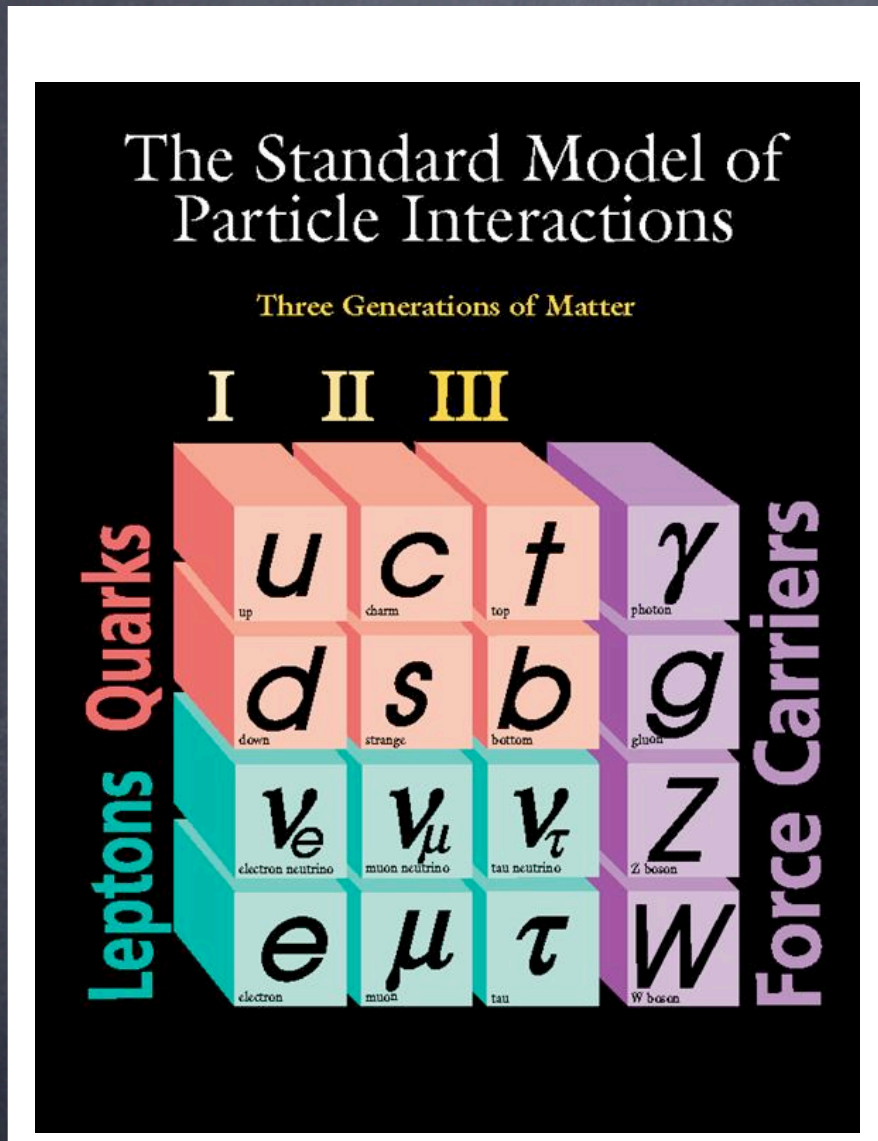
New force!

Standard Model + Supersymmetry + $U(1)$ gauge

(Particles and interactions are fixed)

(Depending on details,
many versions of Supersymmetric models)

New force carrier : Z'



Masses

no mass

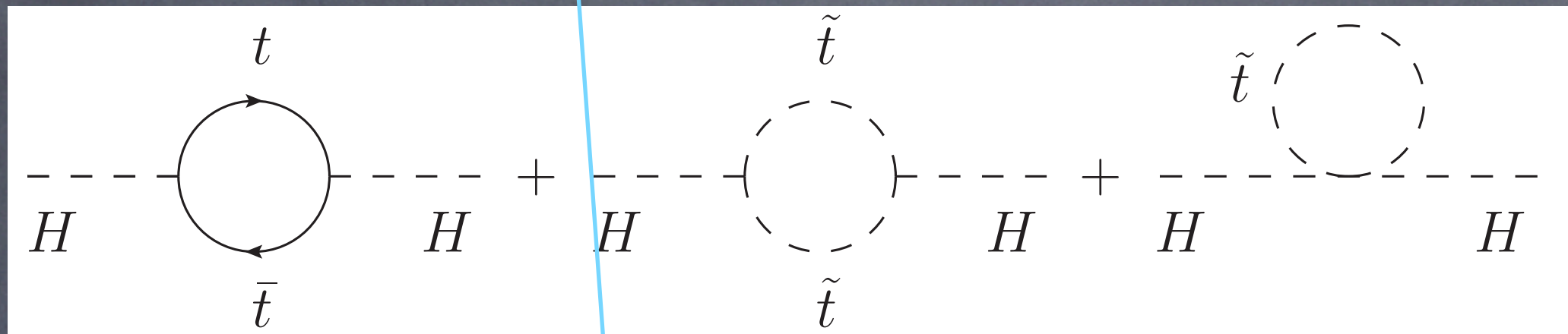
no mass

≈ 100 GeV

≈ 100 GeV

How heavy?

Superpartner mass $\approx Z'$ mass



$$\begin{aligned}\delta m_H^2(\text{top} + \text{stop}) &= (-\Lambda^2 + \dots) + (\Lambda^2 + \dots) \\ &= -m_{\tilde{t}}^2 \log(\Lambda/m_{\tilde{t}}) + \dots\end{aligned}$$

D -term contribution to scalar masses :

$$\Delta m_{\tilde{f}}^2 = \left(\frac{2}{3} \sin^2 \theta_W \cos 2\beta\right) M_Z^2 + (Q'[f]Q'[S]) M_{Z'}^2,$$

If Z' mass $\gg 100$ GeV

→ Superpartner mass $\gg 100$ GeV

→ Higgs Hierarchy problem comes back!

Z' mass should be $O(100 \text{ GeV}) \sim O(1000 \text{ GeV})$!

(1 TeV = 1000 GeV)

Welcome, Large Hadron Collider!



This is why the currently operating LHC is a perfect place to hunt for Z' .

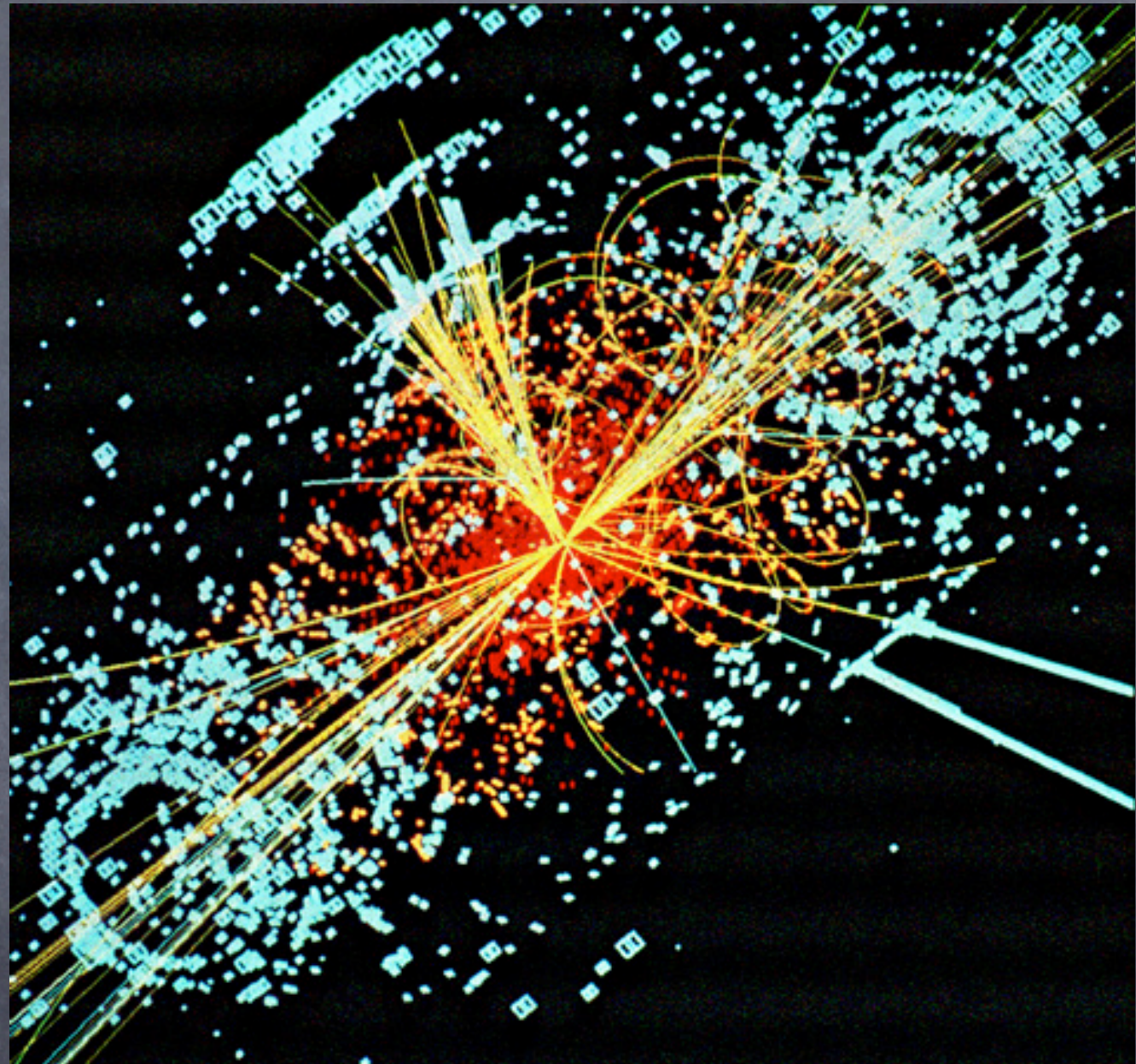
LHC (maximum energy = 14 TeV) probes a TeV scale Z' .

LHC: Proton-Proton Collider

Proton
(7 TeV)



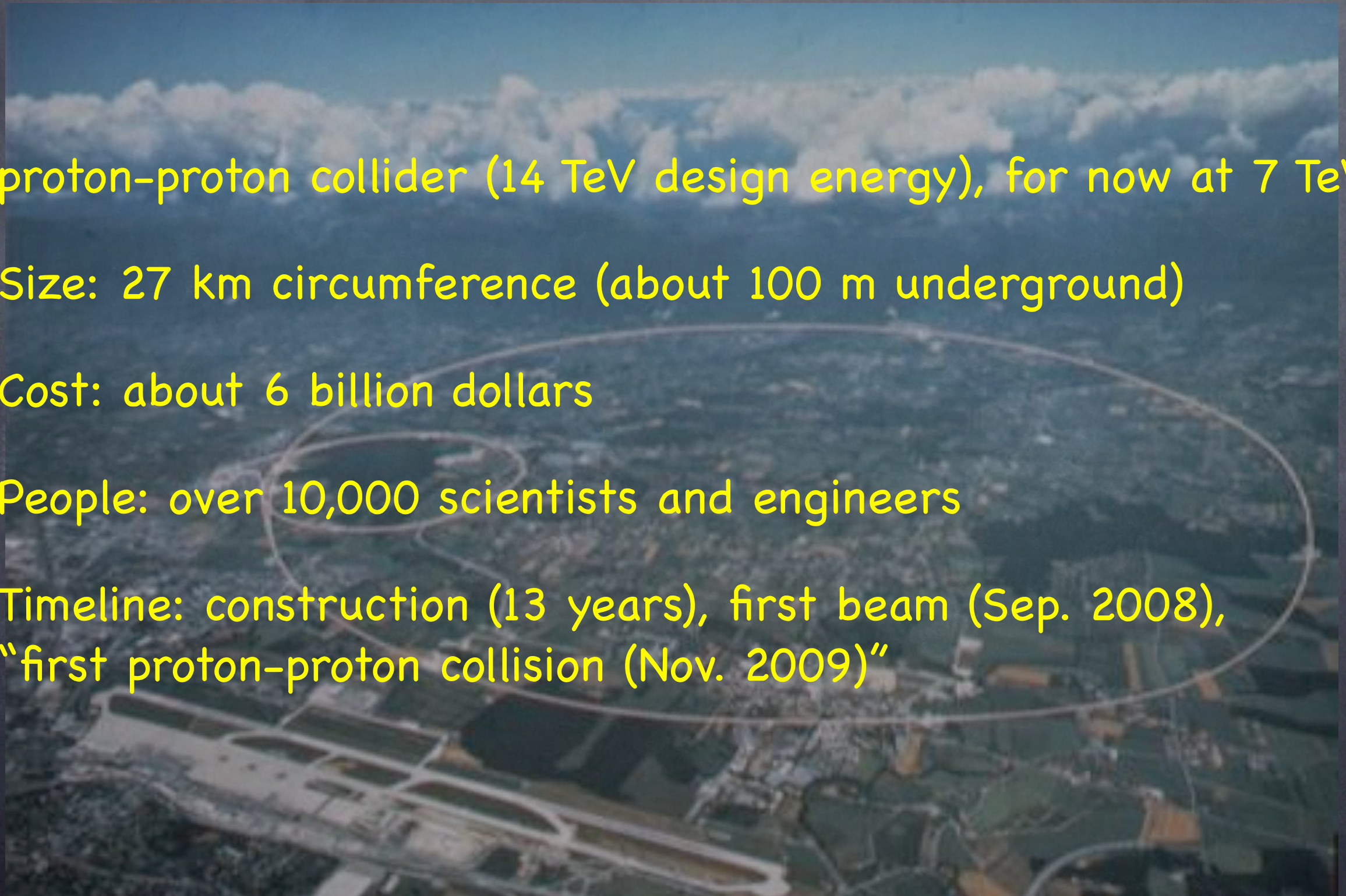
Proton
(7 TeV)



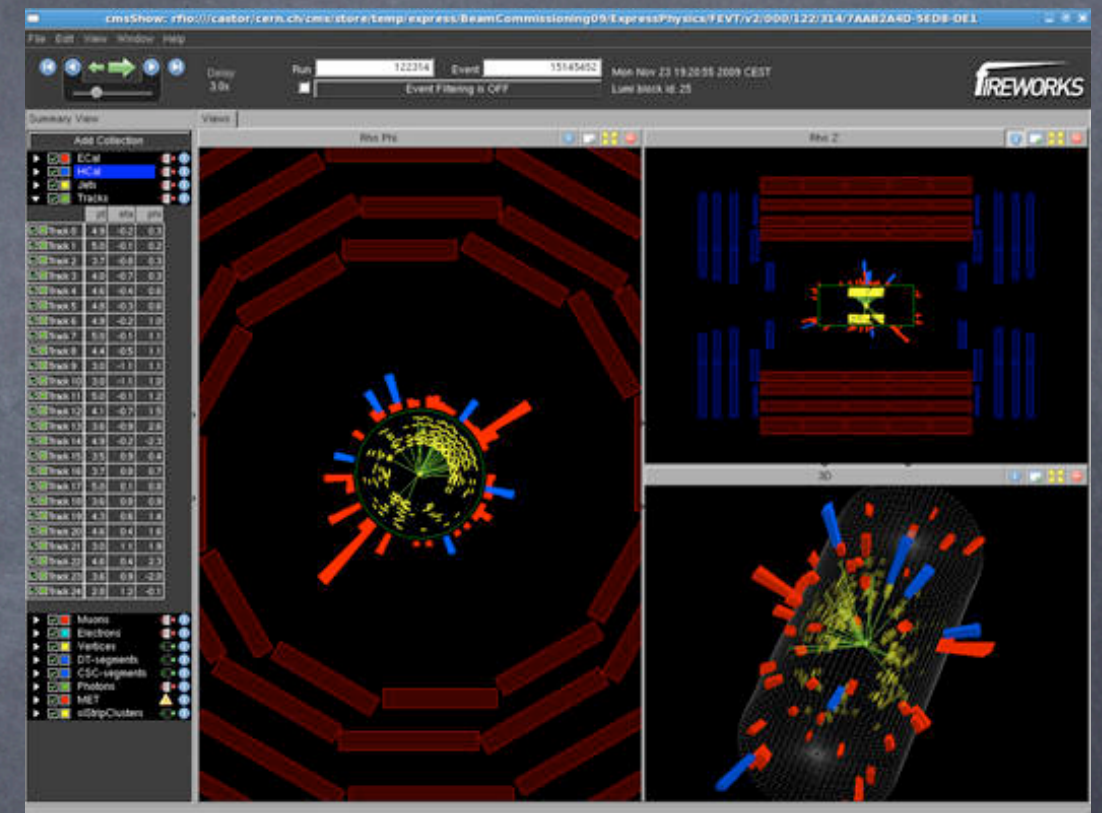
Collision reveals particle physics

Large Hadron Collider (LHC) in Geneva, Switzerland

- proton-proton collider (14 TeV design energy), for now at 7 TeV
- Size: 27 km circumference (about 100 m underground)
- Cost: about 6 billion dollars
- People: over 10,000 scientists and engineers
- Timeline: construction (13 years), first beam (Sep. 2008),
“first proton-proton collision (Nov. 2009)”



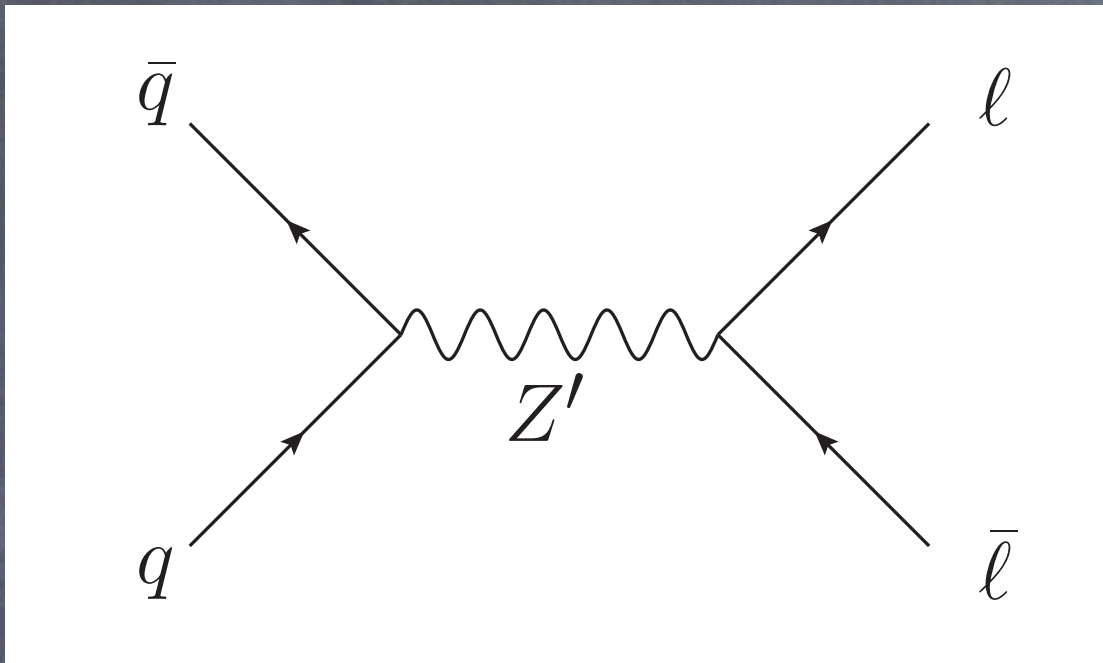
First proton-proton collision at LHC



Nov. 23, 2009

Physicists experiencing a moment of *Joy* at the first collision at the LHC

Discovering Z' at LHC

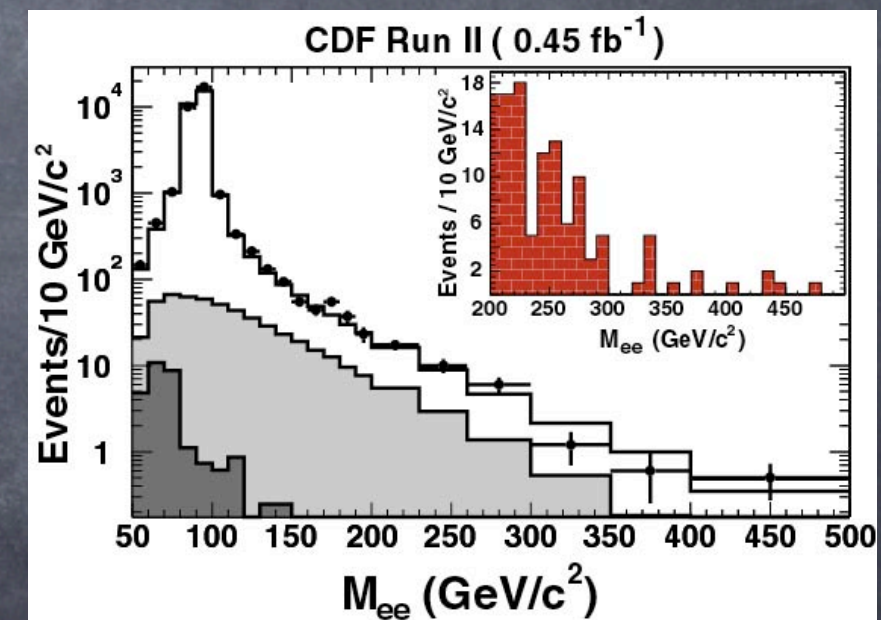


(e^+e^- or $\mu^+\mu^-$)

Dilepton Z' resonance is very likely to be the **first discovery** because of
(i) enhanced cross section,
(ii) clean leptonic signal.

(Irreducible BKG for leptonic resonance is small.)

SM Z boson (91 GeV) at Tevatron



Expect Z' boson at LHC

3. What can we do with
a New force at LHC?
(Overview of my LHC research)

Best-motivated Supersymmetric model

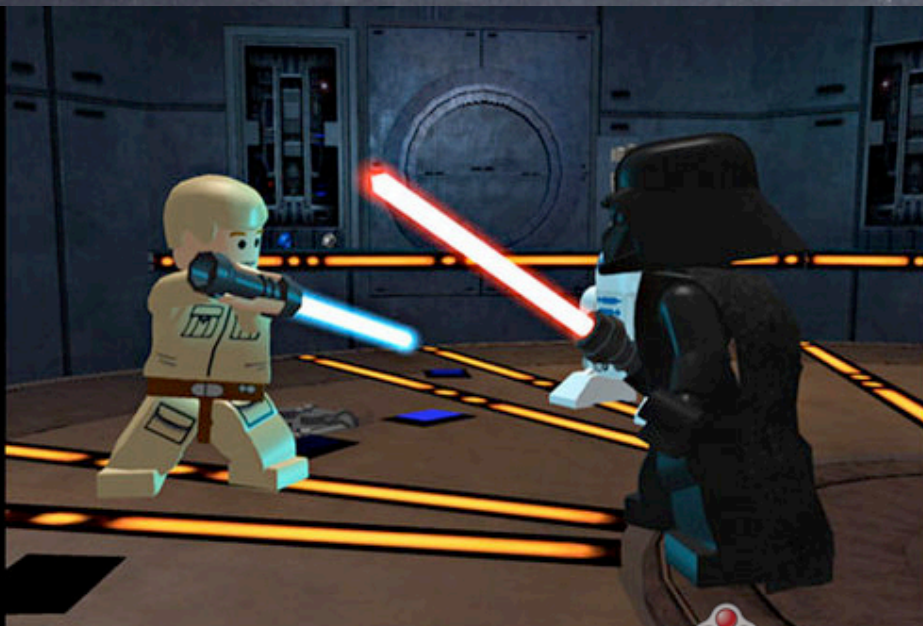
Standard Model + Supersymmetry + U(1) gauge



TeV scale

(Higgs mass \approx Superpartner mass \approx Z' mass)

With a New FORCE,
you can do many things.

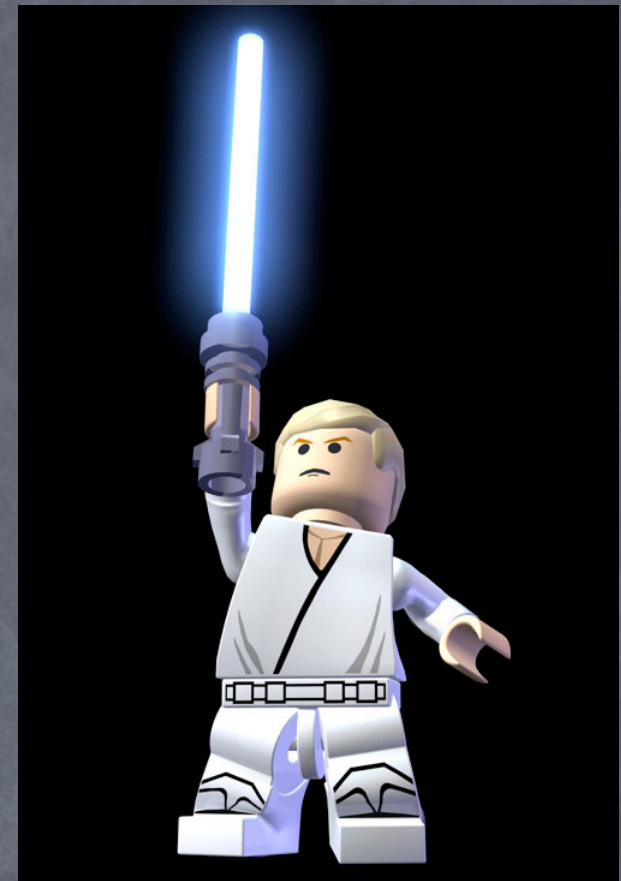


With a New FORCE,
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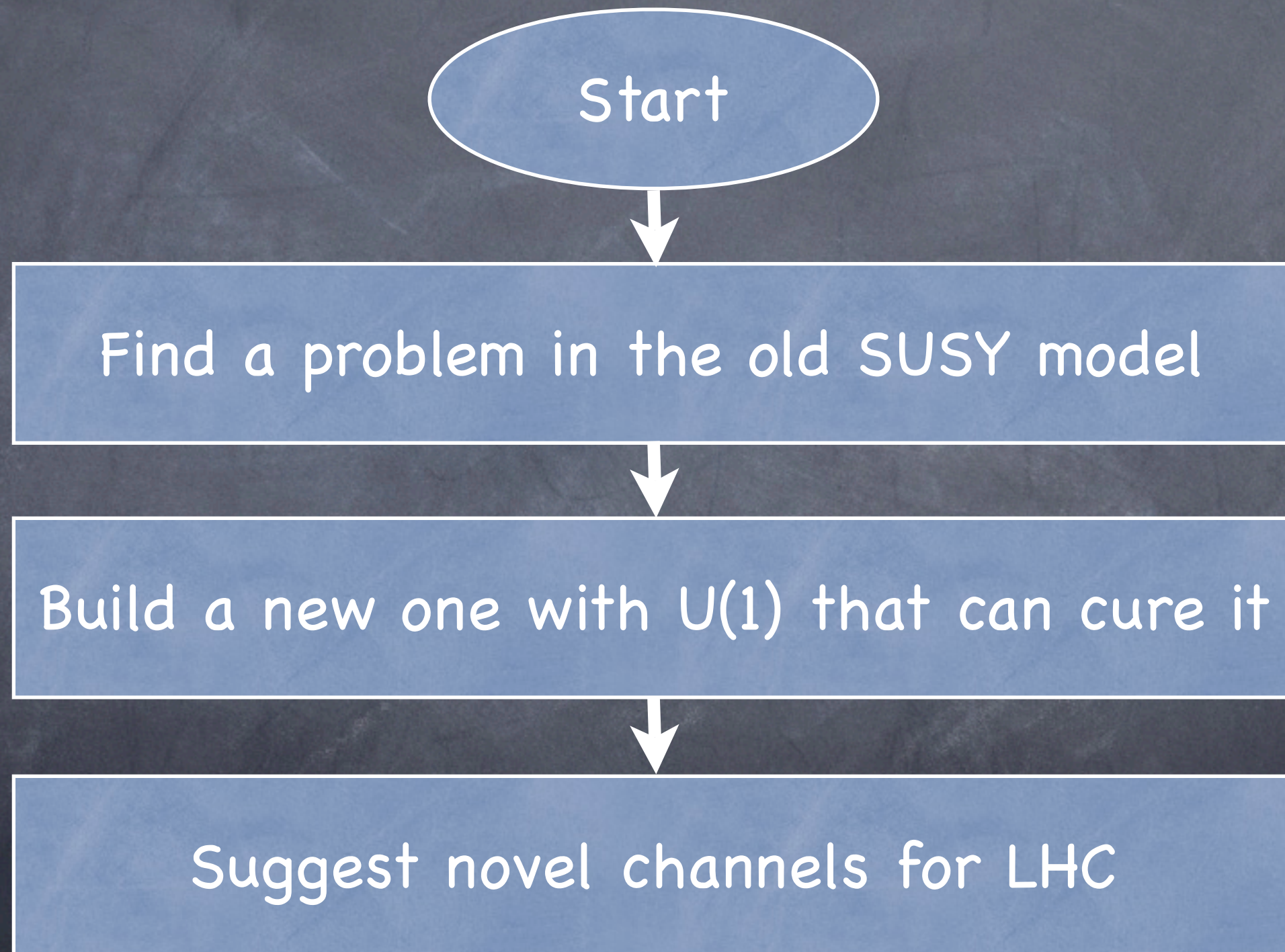
Higgs
B-physics
Cosmology
Nucleon stability
Dark matter search
“LHC phenomenology”

...

Re-visit old SUSY analyses
with a New force.
(Get distinguishable predictions)

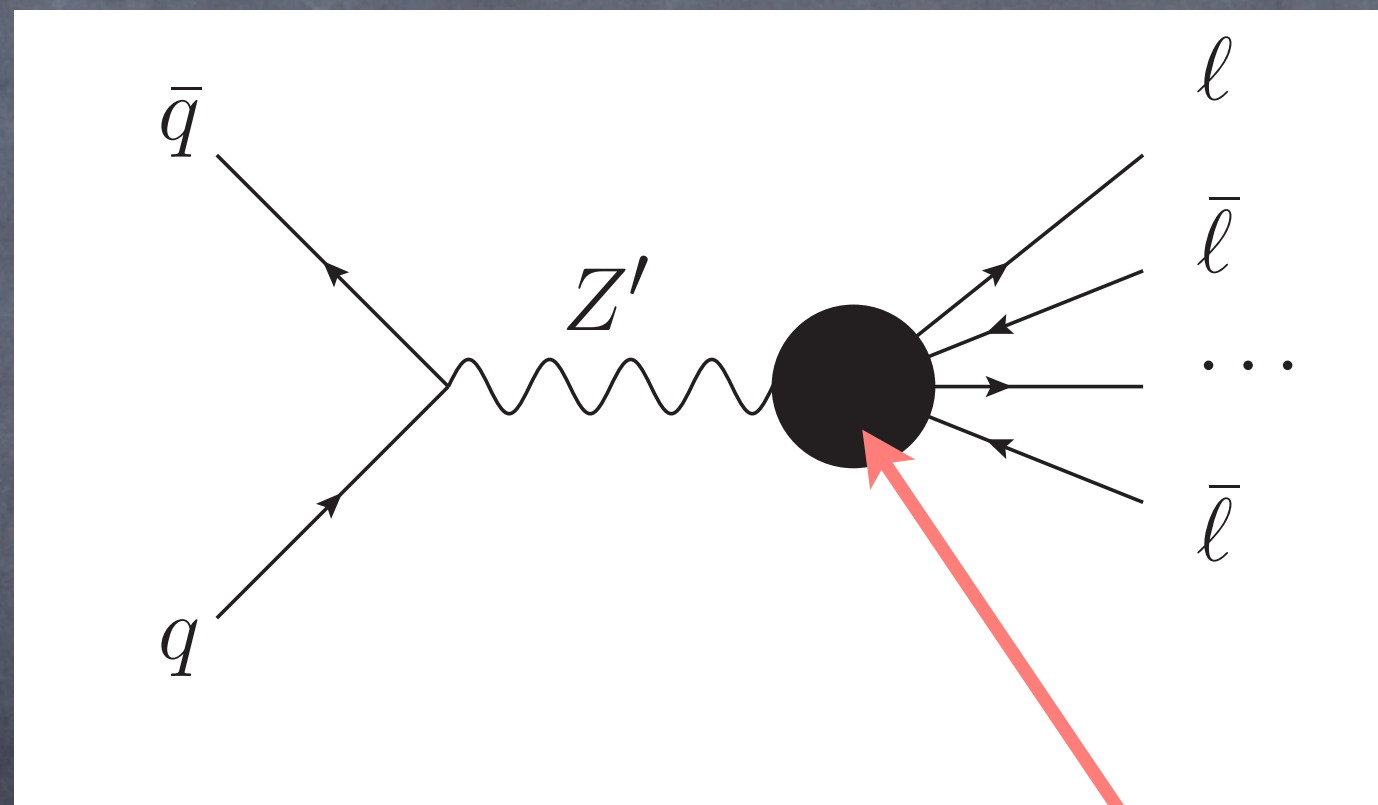


Our approach to LHC physics



Using Z' as a discovery tool

Specifically, we use various leptonic (e, μ) Z' resonances for “other new physics” search.



(flavor-dependent) 2-lepton, 4-lepton, 6-lepton, ...
 Z' resonances (at the LHC)

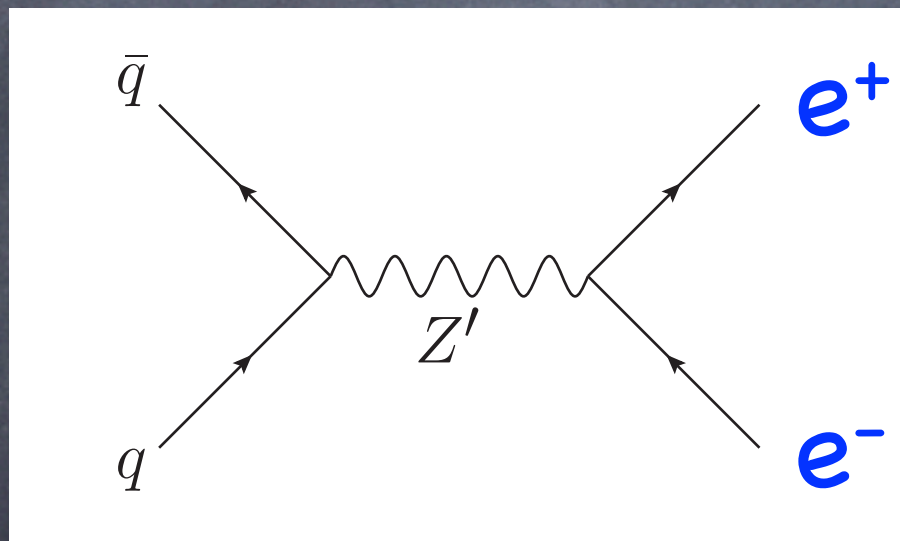
new particle
(Higgs, Superpartner)
in the middle

(i) Flavor-dependent Z' search

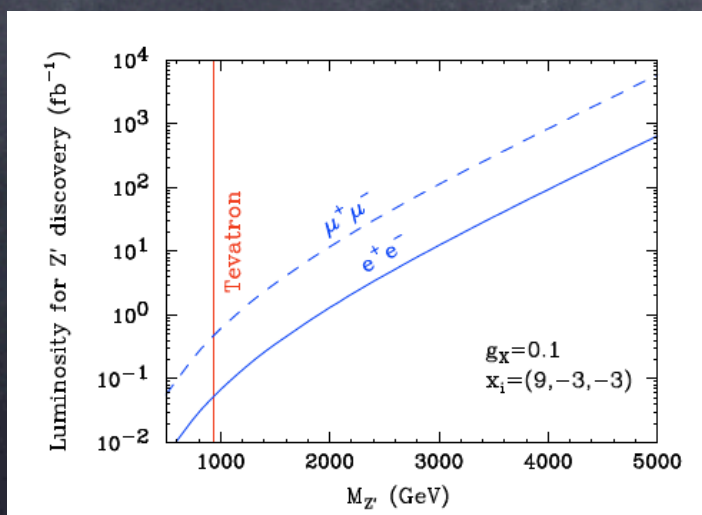
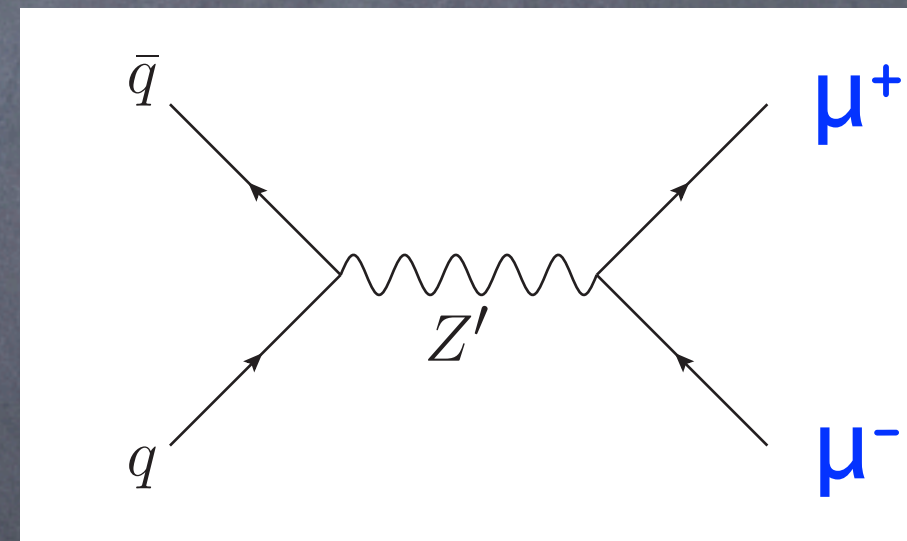
[HL, Ma (2010)]

2-lepton
resonance

- R-parity and $U(1)_{[B-L]}$ (typically used gauge origin of R-parity)
 - Proton : Still decays fast (by non-renormalizable terms).
- Flavor-dependent gauge origin of R-parity : $U(1)_{[B-\xi L]}$ (R-parity is a subgroup)
 - Proton : Sufficiently stable.
 - Character : Z' couples differently to different leptons (electron, muon, tau).



\neq



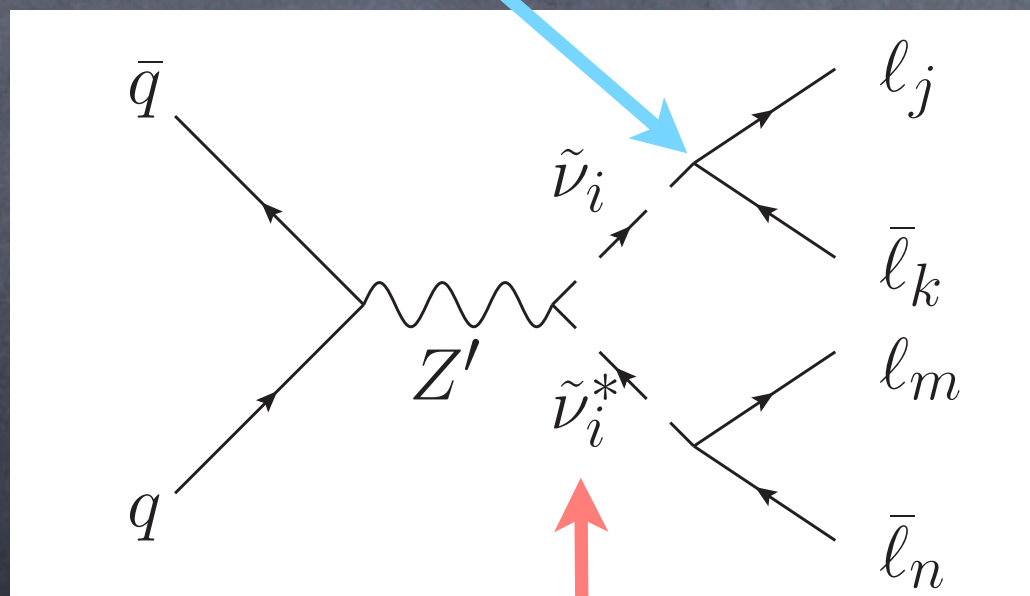
(ex) $(e^+e^- \text{ events}) = 9 \times (\mu^+\mu^- \text{ events})$
[Details omitted]

(ii) Supersymmetry search

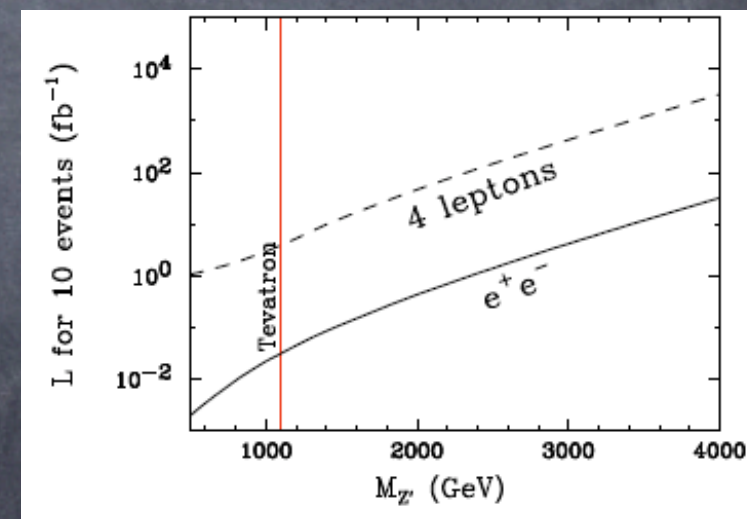
[HL (PLB 2009)]

4-lepton
resonance

- R-parity
 - Proton : Still decays fast.
 - Dark matter : Lightest Superpartner (stable by R_2).
 - Character : Unnecessarily forbid both Baryon # and Lepton # violations.
- Give up R-parity : $U(1)_{[B_3 \times U_2]}$ (B_3 and U_2 are subgroups)
 - Proton : Proton decay ($\Delta B=1$) never occurs. (selection rule of B_3 : $\Delta B=3 \times \text{integer}$)
 - Dark matter : Hidden sector particle (stable by U_2), which satisfies all DM property.
 - Character : Lepton # is freely violated.



Lightest Superpartner
(sneutrino)



(ex) $L=13 \text{ fb}^{-1}$ for $M_{Z'}=1500 \text{ GeV}$
[Details omitted]

(ii) Supersymmetry search

[HL (PLB 2009)]

4-lepton
resonance

- R-parity

- Production: Still depends on

- Decay

- Conservation

- Given

- Production

- Decay

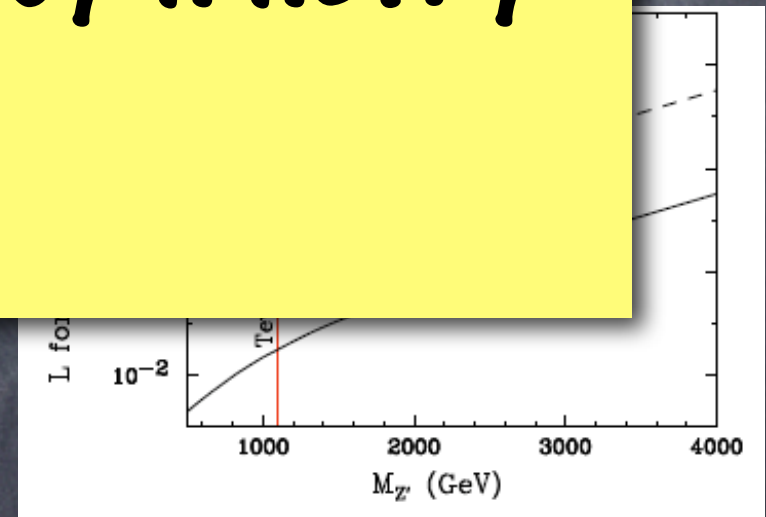
- Conservation

The point is

New force can help Supersymmetry search at the LHC.



Lightest Superpartner
(sneutrino)



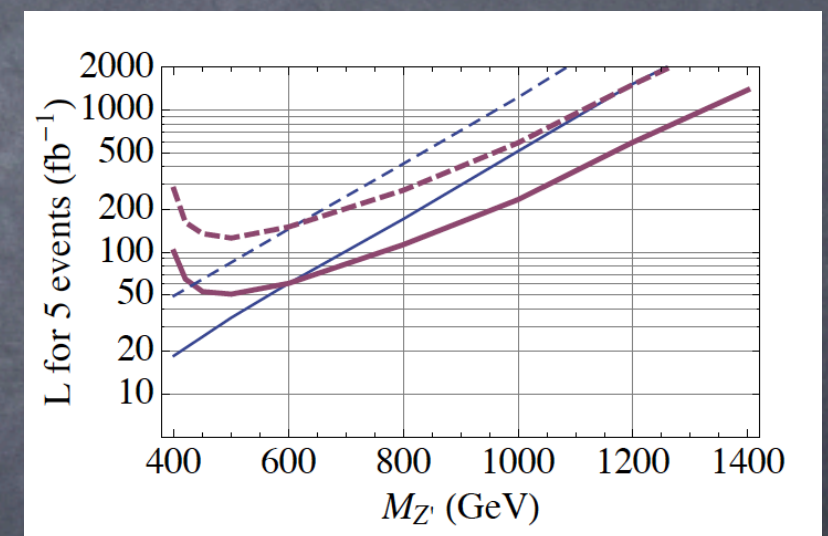
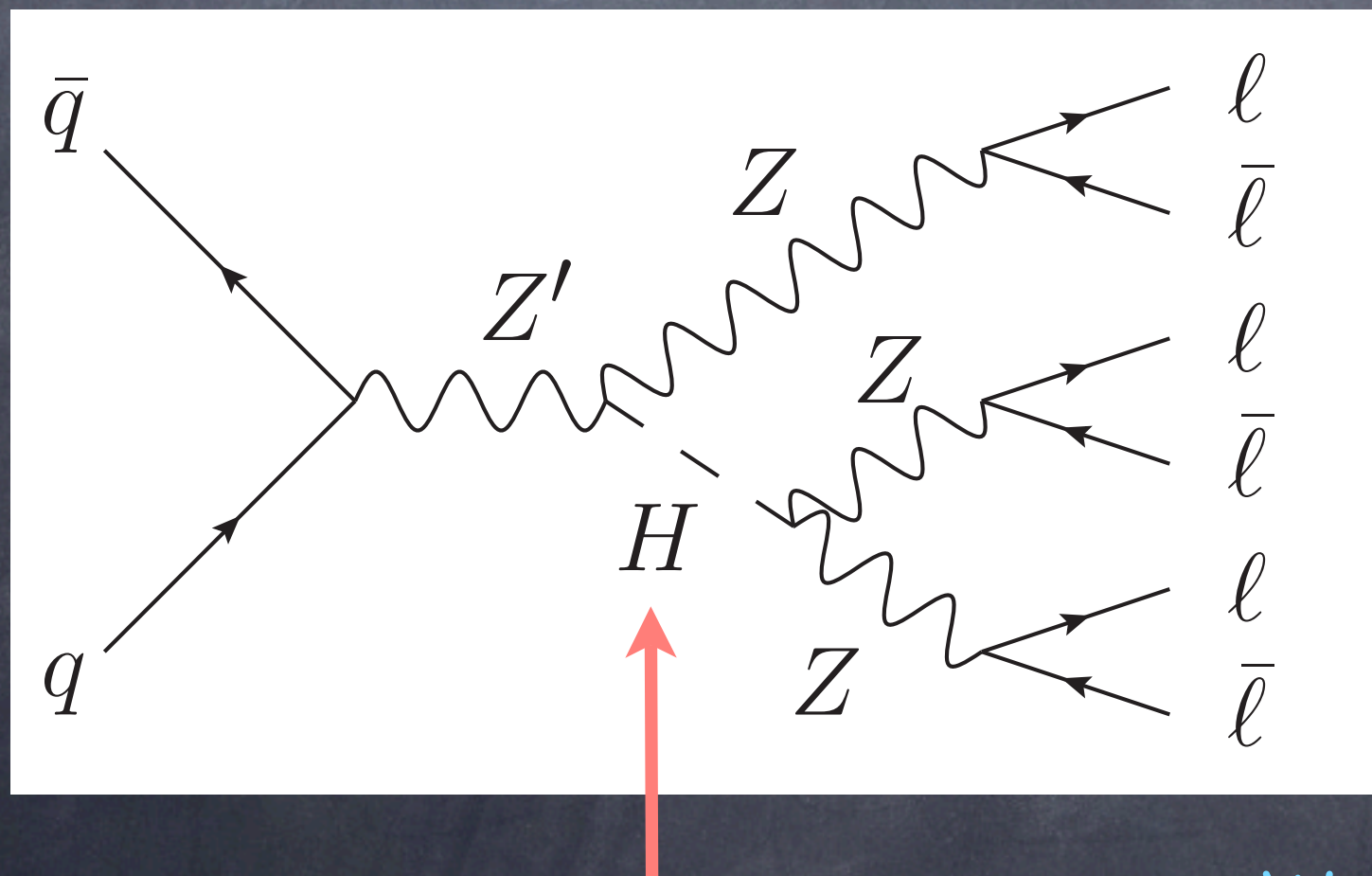
(ex) $L=13$ fb $^{-1}$ for $M_{Z'}=1500$ GeV
[Details omitted]

(iii) Higgs search

[Barger, Langacker, HL (PRL 2009)]

6-lepton
resonance

- Any U(1) (The process does not need Supersymmetry)
 - Z' -Z-H coupling is sizable if Higgs doublet has U(1) charges.
 - Character : Does not require direct Z' coupling to leptons.
(Complementary to dilepton Z' search to discover lepto-phobic Z')



(ex) $L=60 \text{ fb}^{-1}$ for $M_{Z'}=600 \text{ GeV}$
[Details omitted]

Higgs

Works for even
leptophobic Z'

(iii) Higgs search

[Barger, Langacker, HL (PRL 2009)]

6-lepton
resonance

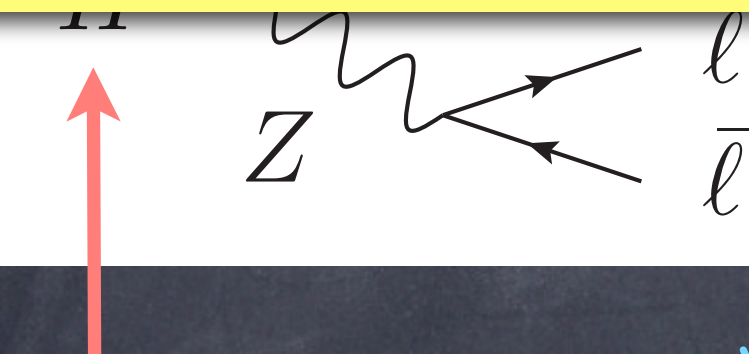
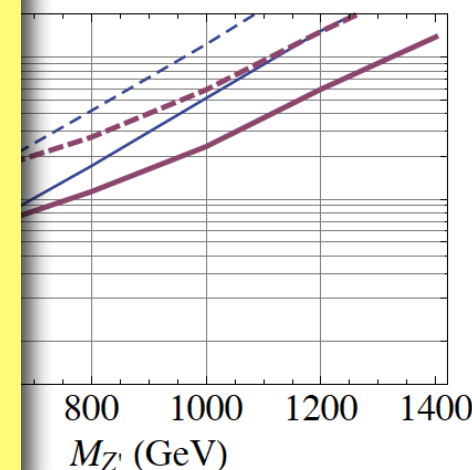
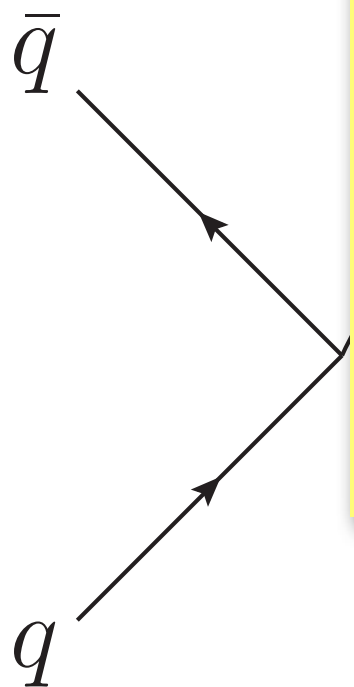
- Any U(1) (The process does not need Supersymmetry)

- Z'-Z-H cou
- Character :

The point is

New force can help Higgs
search at the LHC.

hobic Z')



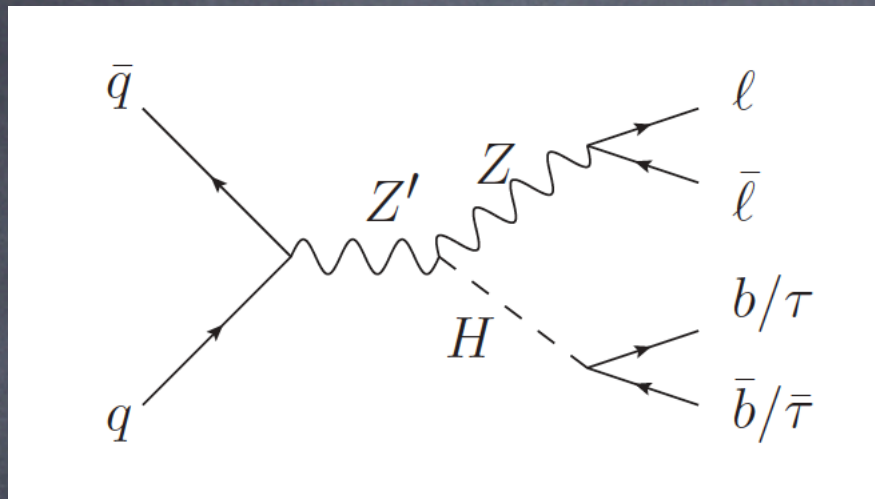
Higgs

(ex) $L=60 \text{ fb}^{-1}$ for $M_{Z'}=600 \text{ GeV}$
[Details omitted]

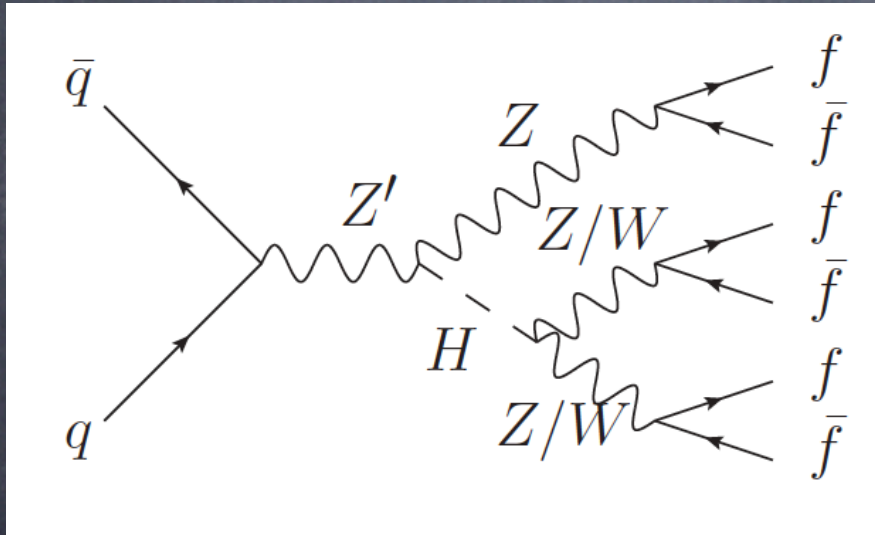
Works for even
leptophobic Z'

(iv) More channels for Higgs search

[Works in future]



2-lepton + 2b/2 τ -jet resonance
: search for a light Higgs



2-lepton + 2Z/2W resonance
: search for a heavy Higgs

and keeps going...

New dark matter candidates with a New force (Z')

1. New neutralino (Z' -ino) dark matter
[Barger, Langacker, HL (PLB 2005)]
2. Sneutrino dark matter
[HL, Matchev, Nasri (PRD 2007)]
3. Hidden sector dark matter
[HL (PLB 2008)]
4. Multiple dark matters
[Hur, HL, Nasri (PRD 2008)]

Variety of DM candidates with Distinguishable properties

Summary

(1) New force carrier Z' (TeV scale) is well-motivated.

Higgs \rightarrow Supersymmetry \rightarrow U(1)

(2) Z' is very likely to be the first discovery at LHC.

(3) Many previous SUSY analysis should be revisited.

Huge research opportunity: 7400 papers with Supersymmetry title

(4) Z' is useful to discover other New particles.

Search for Higgs, Supersymmetry early at LHC



Similarity between Physics and Lotto



Physics is Joyful. It is like Lotto!

Thank you.